
REPORT No. 87

EFFECTS OF NATURE OF COOLING SURFACE ON RADIATOR PERFORMANCE

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RÉSUMÉ.

This report describes an investigation of effects of nature of cooling surface on radiator performance, conducted for the National Advisory Committee for Aeronautics at the Bureau of Standards.

Cooling surfaces in radiators should be kept clean.

An accumulation of oil and dust on the surface will have a very harmful effect on the performance of the radiator.

The following remarks apply only to conditions in which the cooling surfaces are reasonably clean:

1. Heat transfer from an ordinarily smooth surface may be increased 17 per cent for a given air flow, by giving the surface a high polish; or it may be decreased 10 per cent or more by smoking the surface; but
2. Surfaces likely to be obtained in radiators, if fairly clean, will not differ in smoothness enough to give appreciable difference in heat transfer, with a given flow of air through the core.
3. Heat transfer from a radiator may be considerably decreased if the surfaces are not kept reasonably clean.
4. Heat transfer from a radiator (at a given airplane speed) may be slightly increased if special attention is given to smoothness of surface, on account of a small increase in air flow through the core.
5. Heat transfer is practically unaffected by a light coating of clean oil on a smooth surface.
6. Pressure gradient is practically independent of the roughness of the surface over a considerable range.
7. Pressure gradient is practically unaffected by a light coating of clean oil on a smooth surface.
8. Head resistance of a radiator may be slightly decreased by polishing the surfaces (8 per cent observed in one case).
9. Flow of air through the core of a radiator may be somewhat increased by polishing the surfaces (5 per cent observed in one case).
10. Figure of merit of a radiator may be somewhat increased by polishing the surfaces (6 to 10 per cent observed in one case).
11. In general, the performance of a radiator may be improved by polishing the surfaces; but if they are fairly smooth *and clean*, a considerable polish is required to produce much change in the properties of the radiator, and there is a question whether or not such a method for improvement be practicable.

Since the performance of an aircraft radiator depends upon its capacity for transfer of heat from cooling surfaces to moving air, and upon resistance offered to the passage of the air stream, it follows that the nature of the cooling surfaces is a factor worthy of consideration in connection with the properties of the radiator. For direct cooling surface, i. e., for surface backed by flowing water, the effect on heat transfer of the composition of the metal need not be considered, except as one metal is capable of taking a better surface than another, because almost

any metal will conduct heat through the thin walls of the water tubes as rapidly as it can be transferred from the surface of the tubes to the air. The composition and the thickness of the metal are of some importance in the case of surface not backed by flowing water, but it will not be considered here, as this report will deal only with the mechanical condition of the surface.

It will be shown that the degree of roughness or smoothness of the surface is capable of causing important effects on rate of heat transfer and on head resistance, but that in actual radiators having fairly clean surfaces, the differences between various degrees of smoothness are not sufficient to give the effects on radiator properties that might be obtained if it were practicable to have the surfaces highly polished. If, however, the cooling surfaces become coated with oil and dust, the decrease in rate of heat transfer may be very great.

The experimental work on which this report is based consisted of the following measurements, which are described in detail below:

- I. Heat transfer from a single tube, with different conditions of surface.
- II. Heat transfer from two radiators, each with rough and somewhat smoothed surfaces.
- III. Pressure drop in a single tube with different conditions of surface.
- IV. Pressure drop in two radiators of similar construction, but one with rough, and the other with somewhat smoothed, surfaces.
- V. Head resistance of one radiator section, before and after the surfaces had been somewhat smoothed.
- VI. Mass flow of air through the core of one radiator section, before and after the surfaces had been somewhat smoothed.

I. EFFECT OF SURFACE ON HEAT TRANSFER FROM A SINGLE TUBE.

The tube used was of brass, 41.5 cm. (16.3 inches) long, with an inside diameter of 7.8 mm. (0.31 inch), and with walls approximately 1 mm. (0.04 inch) thick. Eight thermocouples were soldered into shallow slots on the outside of the tube, at points 2, 7, 12, and 17 cm. from the ends, and heat was supplied electrically from a coil of No. 32 copper wire wound closely the entire length of the tube, and carefully insulated with baked shellac. The tube was wrapped in hair felt with a corrugated paper covering to within 1 cm. of each end; and the ends were wrapped with several layers of friction tape and inserted tightly into two wooden boxes or chambers in which the properties of the air could be measured as it entered and left the tube. These chambers were 7.6 cm. (3 inches) square and 15.2 cm. (6 inches) long, and each was divided into three compartments by screens. The air entering the first compartment of the inlet chamber passed through a series of screens of coarse mesh wire and finally through a thin screen of hair felt into the second compartment, where its temperature was measured. It then passed through another screen into a third compartment, into which the end of the tube projected about 1 mm. (0.04 inch). This compartment was connected to one side of a vertical oil gauge used to measure the pressure drop through the tube. On leaving the tube, the air passed through the first compartment of the exit chamber, which was connected to the other side of the oil gauge, and then through a screen of wire and a layer of hair felt into the thermometer section, and finally through another screen into the last compartment, which was connected to the inlet of the fan. The exit chamber was very carefully lagged with 2.5 cm. of cork on the outside and 0.5 cm. of hair felt on the inside to prevent the turbulent air from striking the wooden walls directly.

The mass of air flowing through the tube was computed from the heat input to the coil, the rise in temperature of the air and the specific heat of the air—that is, by using the tube itself as a Thomas meter—with the exception that pressure drop through the tube was used for some of the runs after it had been calibrated against the tube as a Thomas meter. The pressure drop method was used in some of the earlier runs when mercury thermometers were used to measure the temperature rise, but was abandoned when thermocouples were used for this measurement. The thermocouples were read on a "pyrovolt," and the heat input to the coil was obtained from readings of a voltmeter and an ammeter.

Care was taken to obtain steady temperature conditions before beginning any set of readings.

Five conditions of surface were used, viz:

1. Original surface (as the tube was drawn).
2. Surface polished (considerable time and effort were expended in getting a high degree of polish).
3. Polished surface lightly oiled.
4. Polished surface lightly smoked.
5. Surface roughened with fine sandpaper.

The results are shown in Plot 1 and in the following table, which shows heat transfer in watts per degree centigrade of difference between the mean temperature of the tube and the temperature of the entering air, and per cent of increase or decrease of heat transfer over that for the original surface:

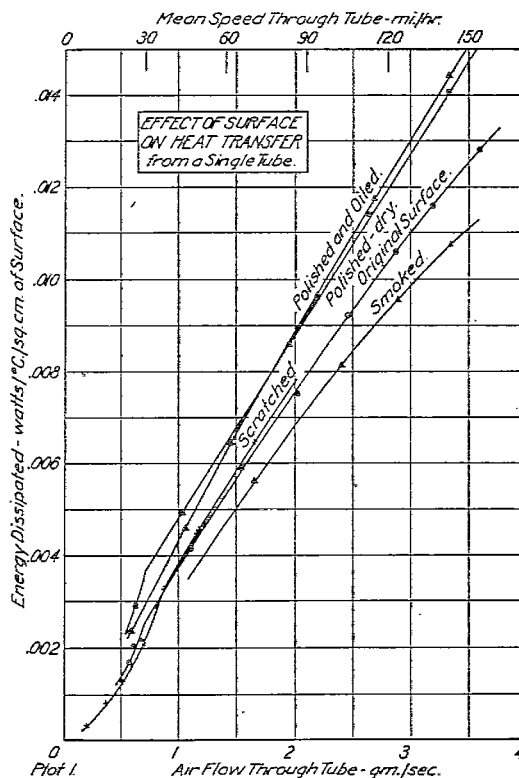
Heat transfer.

[In watts per °C.]

Air flow gm./sec.	Original.	Polished.	Oiled.	Smoked.	Rough.
1	0.378	0.457 + 21.8%	0.417 + 10.3%	0.335 - 11.4%	0.390 + 3.2%
2	.752	.888 + 18.6%	.812 + 7.7%	.688 - 8.8%	.780 + 3.7%
3	1.10	1.30 + 18.2%	1.20 + 9.1%	.988 - 10.2%	1.14 + 3.6%

The table shows the following points:

1. The highly polished surface dissipated about 17 per cent more heat (at the higher speeds) than one fairly rough.
2. The smoked surface dissipated about 10 per cent less heat than the fairly rough one.
3. Oiling the polished surface had very little effect on its heat transfer.
4. The roughened surface was not much different in its heat transfer from the original surface.

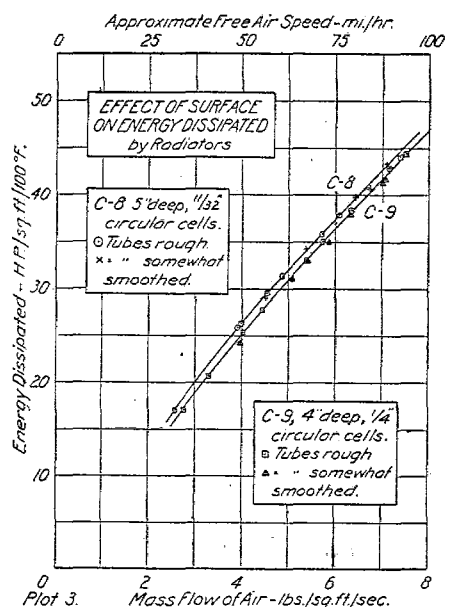


The considerable difference in heat transfer between the fairly rough and the highly polished surfaces may be accounted for by the fact that roughness allows a blanket of more or less stagnant

air to cling to the surface, and thereby to some extent prevents the scouring of the surface that is required for the most rapid transfer of heat.

II. EFFECT OF SURFACE ON HEAT TRANSFER FROM A RADIATOR.

The usual test of heat transfer in terms of air flow was made on two radiator sections 4 and 5 inches (10.2 and 12.7 cm.) deep, and with $\frac{1}{4}$ -inch and $\frac{1}{2}$ -inch (0.64 cm. and 0.87 cm.) circular cells, respectively, each before and after the cooling surfaces had been somewhat smoothed. The original surfaces were considerably rougher than those of many well-made radiators, and the smoothed surfaces were somewhat better than those usually found in radiators, but did not even approximate to the high polish obtained in the single tube mentioned above. The curves, shown in Plot 3, indicate no difference in heat transfer greater than the limit of experimental error, and it appears that although it is possible to increase the heat transfer considerably by giving the surfaces a high polish, it is nevertheless true that any surface likely to be obtained in commercial production will not have a sufficiently high polish to take advantage of this fact.



III. EFFECT OF SURFACE ON PRESSURE GRADIENT IN A SINGLE TUBE.

A brass tube 105 cm. (41.3 inches) in length and with an inside diameter of 0.95 cm. ($\frac{3}{8}$ inch) was used for the measurement of pressure drop with different conditions of surface. Small holes were drilled in the tube at 10-cm. intervals beginning 5 cm. from each end, and tubes were attached to read static pressure at each of these 11 positions. Since it was necessary to remove the burr from the inside of the tube after the holes were drilled, the original surface was not used, and the first measurements were made with the tube polished, though not to the same degree as that obtained in the tube used for heat transfer.

The air flow was measured by means of a small Thomas meter made for that purpose. The meter was made with considerable care, and while it was not calibrated, because of the lack of convenient apparatus, it was without doubt good for comparative purposes at least.

Pressure gradients were obtained by plotting the pressures read at the 11 static holes against their respective positions, and were expressed in grams per square centimeter per centimeter length of tube. The observations on the smoothed and oiled surfaces were very consistent, but when the tube was smoked or roughened the observations were less consistent, probably because of effects of the smoking and the roughening on the static-pressure openings. The errors due to irregularities, however, do not exceed 2 per cent. Corrections for the effect of changing density of the air ranged around 1 per cent and were omitted.

The pressure gradient for a given surface is very nearly proportional to the square of the air flow, and for purposes of comparison a constant " k " was computed for the equation

$$P = kM^2$$

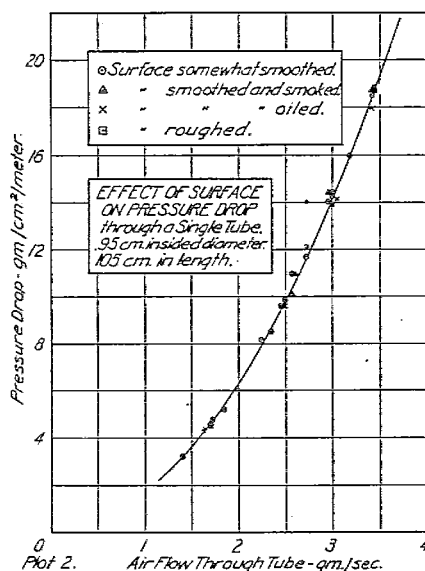
where P = pressure gradient in gm. per sq. cm. per cm., and

M = air flow in gm. per sec.

The mean value of this constant for each surface is tabulated below, together with the per cent of difference from the constant of the smoothed surface. These differences are within the range of experimental error, with the possible exception of the smoked surface, which would probably have shown a greater difference if the tube had been more thoroughly smoked. The length and small diameter of the tube made the roughening of the surface somewhat inconvenient, and the pressure drop would without doubt have been considerably increased if the surface had been made considerably more rough, as is indicated by the results (described below) of the work on a tube in a radiator. These constants may be interpreted to mean that no noticeable difference in pressure drop is to be expected between different surfaces that vary between fairly wide limits of smoothness. The corresponding values of pressure gradient and air flow are shown in Plot 2.

" k " in equation $P = kM^2$.

Surface.	k	Difference, per cent.
Smoothed.....	0.0159	
Smoothed and oiled.....	.0136	-1.9
Smoothed and smoked.....	.0163	+2.5
Roughened.....	.0158	-0.6



IV. EFFECT OF SURFACE ON PRESSURE GRADIENT IN A TUBE OF A RADIATOR.

Two radiators were used, each 4 inches (10.2 cm.) deep, and with $\frac{1}{4}$ -inch (0.64 cm.) circular cells. The first, with tubes somewhat polished, was one of those mentioned under "Heat transfer from a radiator." The second had very rough tubes, similar to those of the first before they had been smoothed.

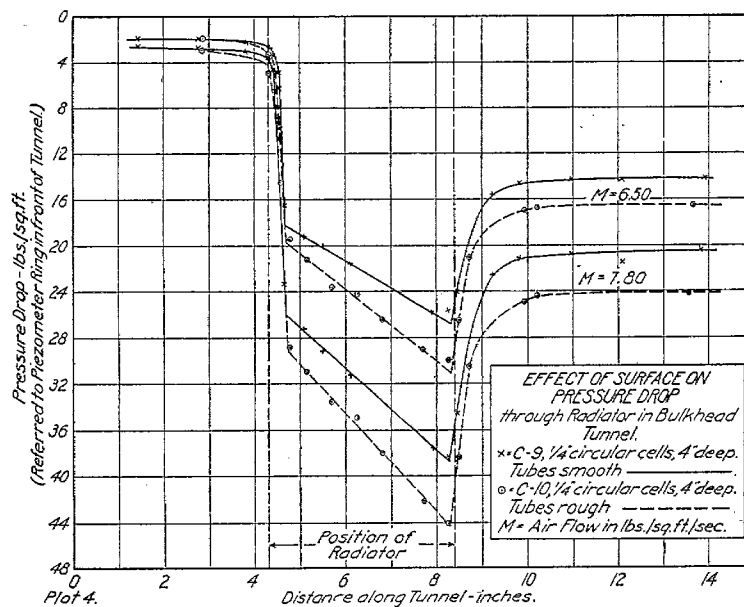
The radiator was placed in the 8 by 8 inch (20.3 cm.) wind tunnel used for measurement of heat transfer, and pressure was measured by means of a steel tube 0.04 inch (1 mm.) in outside diameter and 20 inches (51 cm.) long, with a static-pressure opening near the center. This static-pressure exploring tube was passed through an air tube near the center of the radiator,

and moved forward or backward to obtain the pressure at different positions. It was supported by two pieces of piano wire, which were attached to the ends, stretched over crossbars set in the tunnel 2 or 3 feet in front of and behind the radiator, and carried outside of the tunnel, to facilitate moving the tube forward and backward. One side of an inclined water gage was connected to the rear end of the exploring tube, and the other was connected to a piezometer ring in front of the radiator. It was found by trial that consistent results could be obtained if only ordinary care was used in centering the exploring tube inside of the air tube of the radiator.

Pressure drop between the piezometer ring and the exploring tube was expressed in pounds per square foot; and the air flow, in pounds per second per square foot of frontal area of radiator core. Previous work in a wind tunnel under partial vacuum has shown that the pressure drop between piezometer rings before and behind the radiator is inversely proportional to the air density at the front ring (for a given air flow), and this relation was used to correct for variations in density during the time of the observations.

Curves for two rates of air flow are shown in Plot 4, and the following table shows the values of the pressure gradients inside the radiator tube, both in pounds per square foot per inch, and in grams per square centimeter per centimeter, together with the per cent by which the gradient in the rough tube exceeds that in the smooth tube. The per cent of difference indicated is somewhat too high, because the two radiators were not quite identical, the one with rough tubes having a free area about 3 per cent less, and a head resistance about 7.5 per cent higher, than the other had before its tubes were smoothed.

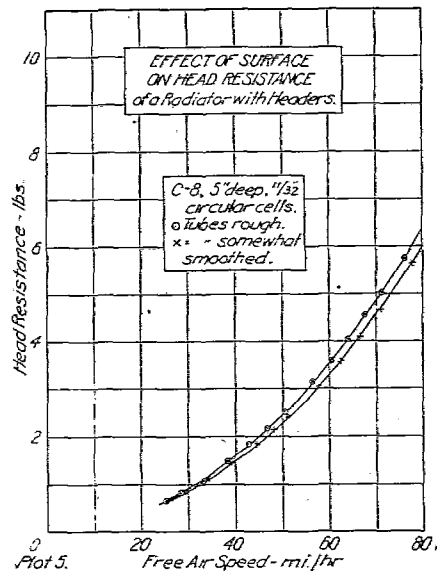
Approximate free air speed, mi./hr.	Air flow, lb./sec. per sq. ft.	Pressure gradient.				Increase, per cent.
		gm./sq. cm. per cm.		lb./sq. ft. per inch.		
		C-9 smoothed.	C-10 rough.	C-9 smoothed.	C-10 rough.	
82	6.50	0.449	0.585	2.34	3.05	30
88	7.00	.512	.664	2.67	3.46	30
99	7.80	.641	.827	3.34	4.81	29



V. EFFECT OF SURFACE ON HEAD RESISTANCE OF A RADIATOR.

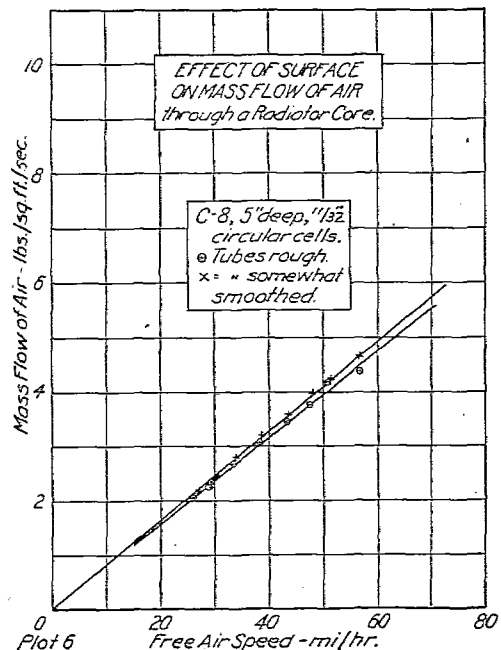
The radiator C-8, 5 inches (12.7 cm.) deep, with $\frac{1}{2}$ -inch (0.87 cm.) circular cells, was also tested for head resistance with the two conditions of surface described under "Heat transfer from a radiator," viz, very rough, and somewhat smoothed. The difference in head resistance

observed—about 6 per cent—is not as great as should be shown, because of the fact that the section used included attached water boxes, and the effect of the water boxes is partially to mask any effect of changes in the core. A good estimate of the change in head resistance may be made by comparing the air flow with Plot 1 of Technical Report 63, Part I, which shows a general relation between head resistance and air flow for radiators with straight air passages. The “mass flow factors” corresponding to the smoothed and rough surfaces were respectively 0.0820 and 0.0790, and the curve shows that the corresponding “head resistance constants” are 0.00153 and 0.00165, which gives a difference of 8 per cent, and is probably correct within 1 per cent. The observed values of head resistance are shown in Plot 5.



VI. EFFECT OF SURFACE ON AIR FLOW THROUGH A RADIATOR.

As implied above, the radiator C-8 was tested not only for head resistance but for mass flow of air through the core, in terms of free air speed. The increase in air flow with the smoothed surface was 5 per cent, and is indicated in Plot 6.



EFFECT OF SURFACE ON FIGURE OF MERIT.

The tests made on the section C-8, 5 inches (12.7 cm.) deep with $\frac{1}{16}$ -inch (0.87 cm.) circular cells, permit a computation of figure of merit with the two conditions of surface. The figure of merit is the ratio of the rate at which the radiator dissipates heat (expressed in horsepower) under specified conditions of temperature and water flow, to the horsepower absorbed by the radiator because of its head resistance and weight. The following results apply to the radiator when in such a position on the airplane that the flow of air through and around the radiator is not affected by other parts of the plane. The per cents of difference are based on the values with the tubes smoothed.

Free air speed, mi./hr.	Figure of merit.		Difference, per cent.
	Rough.	Smooth.	
30	39.2	41.8	6.2
60	19.5	21.4	8.9
90	10.3	11.5	10.3
120	6.0	6.7	10.3

EFFECT ON RADIATOR PERFORMANCE OF OIL AND DUST ON THE COOLING SURFACES.

The tests described above have dealt mainly with the degree of smoothness of the cooling surfaces, and so far as they go, they seem to indicate that in actual radiators the differences between conditions of surface encountered will usually not be great enough to show any very great difference in the properties of the radiators. But the results of these tests should be interpreted with a little caution, for they do not include the condition of surface caused by a coating of oil and dust, such as sometimes occurs in actual radiators. The "oiled" surfaces mentioned above were first polished, and then *lightly* coated with clean oil, and such a surface is evidently not representative of the of the heavy coat of oil and dust that sometimes accumulates. The smoked surface used with the single tube for heat transfer probably gives the nearest approach in the tests, to the condition of surface with oil and dust. Even though the tube was highly polished before being smoked, the lightly smoked surface caused an insulating blanket of smoke particles and nearly stagnant air that was sufficient to reduce the heat transfer to 10 per cent less than that with an ordinary surface; and a coating of oil filled with dust may be expected to cause an insulating blanket that will reduce the heat transfer even more. In fact, it is well known that even in automobiles such a surface interferes with the performance of the radiator.

CONCLUSIONS.

Cooling surfaces in radiators should be kept clean. An accumulation of oil and dust on the surface will have a very harmful effect on the performance of the radiator. The following remarks apply only to conditions in which the surface is reasonably clean.

The lack of any quantitative measure of the condition of the surface complicates the problem of correlating the various results, but in Plot 7 an attempt is made to show the relations between the different quantities, by indicating the per cent of difference between values of heat transfer, pressure drop, etc., corresponding to different conditions of surface. The head and the tail of each arrow indicate the conditions of surface considered, and the arrow points away from the quantity on which the percentage is based. For example, the arrow under "head resistance" indicates that in passing from the smoothed to the very rough surface, head resistance was increased by 8 per cent of its value with the smoothed surface.

The results of the tests may be summarized as follows:

1. The degrees of smoothness usually found in radiators (not including the surface coated with oil and dust) are entirely within the range of the degrees of smoothness covered by most of the tests, so that with a few exceptions the per cents of difference shown in the diagram and in the tables are greater than what would usually be obtained by comparison of different radiators as they come from the manufacturers.

2. Heat transfer from an ordinarily smooth surface may be increased 17 per cent for a given air flow by giving the surface a high polish; or it may be decreased 10 per cent or more by smoking the surface; but

3. Surfaces likely to be obtained in radiators, if fairly clean, will not differ in smoothness enough to give appreciable difference in heat transfer, with a given flow of air through the core.

4. Heat transfer from a radiator may be considerably decreased if the surfaces are not kept reasonably clean.

COMPARATIVE EFFECTS OF CONDITION OF SURFACE								
	SURFACE	HEAT TRANSFER		PRESSURE DROP		HEAD RES.	AIR FLOW	FIG. OF MERIT
		Single Tube	Radiator	Single Tube	Radiator			
Limits of usual Radiator Surfaces.	HIGH POLISH	Oiled	↑					
		Dry	↑					
			+17%	+16%				
	SMOOTHED	Oiled		↑	±0%			
		Dry		↑				
	ORDINARY							
			0%	0%	+25%	0%	less than +30%	+8%
	ROUGHENED							
			-11%					
	VERY ROUGH							
	SMOKED							

Example: - Head resistance with very rough surface is 8 % greater than with smoothed surface.

Note: - This chart applies only to surfaces that are reasonably clean. Plot 7.

5. Heat transfer from a radiator (at a given airplane speed) may be slightly increased if special attention is given to smoothness of surface, on account of a small increase in air flow through the core.

6. Heat transfer is practically unaffected by a light coating of clean oil on a smooth surface.

7. Pressure gradient is practically independent of the roughness of surface over a considerable range.

8. Pressure gradient is practically unaffected by a light coating of clean oil on a smooth surface.

9. Head resistance of a radiator may be somewhat increased by polishing the surfaces (8 per cent observed in one case).

10. Flow of air through the core of a radiator may be somewhat increased by polishing the surfaces (5 per cent observed in one case).

11. Figure of merit of a radiator may be somewhat increased by polishing the surfaces (6 to 10 per cent observed in one case).

12. In general, the performance of a radiator may be improved by polishing the surfaces; but if they are fairly smooth and clean, a considerable polish is required to produce much change in the properties of the radiator, and there is a question whether or not such a method for improvement is practicable.